Medical Geology

Syed E Hasan, Department of Earth and Environmental Sciences, University of Missouri, Kansas City, MO, United States

Glossary

Aerosols Suspension of microscopic size solids, or tiny droplets of liquid, or gas in the air.
***Al Eskan* disease** Recent term for pneumonia acquired from exposure to organic and inorganic substances embedded in dust storms, reported among deployed military personnel in the Middle East. Synonymous with Gulf War syndrome, Persian Gulf syndrome, and desert dust pneumonitis.
Alzheimer's disease A degenerative disease of the brain that results in progressive memory loss, impaired thinking, disorientation, and changes in personality and mood; is the most common form of dementia.
Amylophagy A form of geophagy expressed by compulsive tendency to eat raw starch.
Asbestosis A disease of the lungs caused by inhalation of asbestos fibers that is marked by thickening and scarring of lung tissue.
Astragalus bisulcatus A selenium accumulating shrub.
Balneotherapy Use of mineral water, usually warm-hot for topical skin therapy.
Bioavailable A general term for a particular form of a chemical that can be absorbed in the body.
Blind staggers Is a symptom of several unrelated animal diseases, in which the affected animal walks with an unsteady, staggering gait, and loss of vision. One of the causes includes poisoning from ingesting plants containing a high level of selenium.
Cauterization Medical treatment for rapid formation of scar on wound.
Chronic obstructive pulmonary disease Also referred to as COPD. A pulmonary disease, such as emphysema or chronic bronchitis, that is characterized by irreversible airway obstruction, resulting in pulmonary disease and a reduced rate of exhalation.
Coccidioidomycosis A disease in humans and domestic animals that is caused by inhalation of spores from the fungi *Coccidioides immitis* or *C. posadasii*, found in dry soils.
Cretinism A congenital condition marked by physical stunting and intellectual disability and caused by severe hypothyroidism.

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Crust The upper most layer of the earth, 5–40 km thick, relatively cold (compared to deeper layers) and comprising solid, brittle rocks.
Dental caries Tooth decay marked by progressive destruction of bone or tooth.
Dental fluorosis An abnormal condition (such as mottling of the teeth) caused by fluorine or its compounds.
Dystrophy In general, any condition produced by faulty nutrition; the term is commonly used for a variety of other conditions, particularly conditions that noticeably affect the muscles.
Fibrosis A condition marked by increase of interstitial fibrous tissues.
Gastroenteritis Inflammation of the lining membrane of the stomach and the intestines characterized especially by nausea, vomiting, diarrhea, and cramps.
Gem electuary A medicated paste prepared by pulverizing *gem* stones and mixing it with a sweetening substance, such as honey. Not used on humans any more but still used in veterinary practice, and administered by smearing on the teeth, gums, on tongue.
Geomedicine A branch of medicine that deals with geographic factors in medicine; common use of geospatial methods in spread of disease.
Geopharmaceutical A broad term used for medical formulations in which geological materials are used as ingredients.
Germ theory A theory in medicine, emphasizing that infections, contagious diseases, and other conditions result from the action of microorganisms.
Gout A metabolic disease marked by painful inflammation of the joints, deposits of urates in and around the joints, commonly with an excessive amount of uric acid in the blood.
Hyperthyroidism Excessive functional activity of the thyroid gland that results in increased metabolic rate, enlargement of the thyroid gland, rapid heart rate, and high blood pressure.
Intertrigo Inflammation produced by chafing of adjacent areas of skin.
Isopods Any species of a large order (Isopoda) of small immobile aquatic or terrestrial crustaceans.
Keratosis Area of skin marked by overgrowth of horny tissue.
Lassitude A condition of weariness or debility, accompanied by sickness and weight loss.
Lithotherapy An alternative system of medicine that uses the energy and colors of minerals and rocks for healing. The literal meaning of the Greek term is curing by using rocks.
Locosis A disease commonly in horses, mules, cattle, and sheep, caused by chronic poisoning with locoweeds that belong to any of several leguminous plants of the genera *Astragalus* and *Oxytropis*.
Magnitude, earthquake A measure of the energy output or power of the earthquake; the logarithmic magnitude scale ranges from 0 to 10, with each successive number indicating an order of magnitude difference.
Meningococcal meningitis A disease marked by inflammation of the membranes that enclose the brain and spinal cord (the meninges) that is either a relatively mild illness caused by a virus (such as various Coxsackieviruses) or a more severe, usually life-threatening illness, caused by the bacterium (*Neisseria meningitidis*).
Mesothelioma A type of cancer that develops from the thin layer of tissue that covers many of the internal organs (known as the mesothelium). The most common area affected is the lining of the lungs and chest wall. Prolonged exposure to some variety of asbestos family minerals can cause mesothelioma.
Miasmatic theory An old theory used to explain occurrence of disease due to inhalation of air.
Mycosis Disease caused by a fungus (e.g., ring worm, etc.).
Neurogenerative disease A general term for a range of conditions which primarily affect the neurons in the human brain, e.g., Parkinson's disease.
Neuropathy Damage or dysfunction of one or more nerves that typically results in numbness, tingling, muscle weakness, and pain in the affected area.
Non-cirrhotic portal A condition marked by increase of interstitial fibrous tissues in the veins that collect blood from one part of the body and distribute to another, e.g., from stomach to spleen, etc., but not into the liver.
Otitis media An inflammatory diseases of the middle ear, common in children.
Pagophagy Compulsive desire to eat ice (a form of geophagy).
Pica Medical term for craving to eat non-food items such as soil, clay, ice or raw starch.
Pneumoconiosis A disease of the lungs due to inhalation of dust, mineral particles, etc. characterized by inflammation, coughing, and fibrosis.
Pulmonary fibrosis A lung disease that causes the lung tissue to become damaged and thick. The thickened, stiff tissue makes it more difficult for the lung to work properly.
Rheumatism Any of various conditions characterized by inflammation or pain in muscles, joints, or fibrous tissue.
Sarcoidosis An inflammatory disease that affects multiple organs in the body, but mostly the lungs and lymph glands, resulting in the occurrence of abnormal masses of inflamed tissues in the body.
Silicosis Fibrosis of the lung, caused by the inhalation of dust containing silica.
Skeletal fluorosis A bone disease caused by excessive accumulation of fluoride in the bones. In advanced cases, it causes painful damage to bones and joints.

Slag wool A type of mineral wool manufactured from melts of metallurgical slags by converting them into glasslike fibers for thermal insulation.
Syncope Loss of consciousness resulting from insufficient blood flow to the brain.
Urolithiasis A condition that is marked by the formation or presence of mineral salts (calculi) in the urinary tract.
Weathering A geologic process that operates at the earth's surface, resulting in gradual decomposition and disintegration of rocks into discrete mineral grains and constituent chemical elements and compounds; caused by a series of complex chemical, physical, and biochemical reactions.
Zoonotic disease Diseases caused by transfer of a virus from animals to humans, e.g., COVID-19, Ebola, zika, etc.

Nomenclature

M	Metric
MCL	Maximum contaminant level
mg/kg	Milligram per kilogram (=ppm)
mg/L	Milligram per liter (=ppm)
n	Nano (1×10^{-9})
PMs	Particulate matters
ppb	Parts per billion (1×10^{-9})
ppm	Parts per million (1×10^{-6})
μg/kg	Microgram per kilogram (=ppb)
μg/L	Microgram per liter (=ppb)
μgd/L	Microgram per deciliter

Introduction

The health and well-being of humankind are intimately tied to the quality of air, water, and soil, all of which are influenced by the regional and local geology where a population resides. The ultimate source of all chemical elements is the rocks of the Earth: the outermost layer of the earth, called crust, supplies all nutrients. The process of weathering results in gradual breakdown and decomposition of the rock into its constituent minerals, and ultimately into various elements that are released into the environment to supply vital nutrients but sometimes harmful substances as well. This complex and slow geologic process depends on climate of the area, nature of the rock itself, and presence or absence of biota. As a general rule, rate of weathering is faster in warm and moist climatic regions with thriving biota, and slowest in cold regions with no or sparse biota. Additionally, natural geological processes, such as dust storms, volcanic eruptions, and earthquakes, can release enormous quantities of mineral-laden dust, various toxic chemical elements and compounds, and coarse particles into the atmosphere resulting in poor and, often dangerous air quality.

The prevalence of mineral nutrients in the water and soil of an area, their excess or deficiency, is also directly controlled by local geology. Geological materials and processes not only influence human health but also that of plants and animals; and in a broader context all the non-living components of the environment as well. Lately, a new term *planetary health* has been gaining currency, emphasizing that a healthy planet is essential for human health and well-being. Alarming degradation of the natural life-support systems—air water, biota, and soils during the past 200 years, the like of which has never occurred in the Earth's 4.6 billion-year history, has been the driving force behind the planetary health movement. Concerned by the degrading quality of earth's natural systems and its far-reaching consequences on human and ecosystem health, the emerging concept of planetary health emphasizes: ……"*human health and human civilization depend on flourishing natural systems and the wise stewardship of those natural systems*" (Whitmee et al., 2015).

The importance of geologic materials, particularly minerals, as healing agents has been recognized since antiquity. Ancient Chinese and Indian people used minerals for healing as far back as 3000 BC. The Ayurvedic system of Indian medicine utilized minerals, such as cinnabar (HgS), galena (PbS), and realgar (As_4S_4), along with chemical elements such as Au, Ag, Fe, and Zn, often combined with herbs, in medicinal preparations. An early Chinese pharmacopeia includes use of arsenolite (As_2O_3), pearl ($CaCO_3$), and cinnabar (HgS) used for treatment of various ailments. The Assyrians and Babylonians are believed to have used alum $KAl(SO_4)_2.12H_2O$, bitumen, and other natural materials for healing. Ancient Egyptians (1600 BC) used asphalt, copper, iron, lead, potassium nitrate (KNO_3), and sodium carbonate (Na_2CO_3) for medicinal purposes. Greeks and Mayans are also known to have used many minerals in medical prescriptions, about 400 BC and 800 AD, respectively. Islamic medicine flourished between the 8th and 14th centuries. Several Arab scholars made valuable contributions to medicine, notably Rhazes (865–925), Abulcasis (936–1013), and Avicenna (980–1037). Rhazes (Arabic name: Abūbakr Mohammad Zakariyyā Rāzī), was an alchemist, physician, and philosopher from Rayy near Tehran in modern-day Iran. His most famous work, *Kitab al-Hawi fi al-Tibb* (The Comprehensive

Book of Medicine), running into 23 volumes, was translated into Latin in the 13th century. The Latin translation entitled *Liber Continens*, and its first edition, published in Brescia, Italy, in 1486, is the largest and heaviest book printed before 1501. In it, Rhazes described many medicinal formulations using geological materials, such as alum, saltpeter, gold, and mercury for treatment of various medical conditions. Abulcasis (Abū al-Qāsim in Arabic), a distinguished Arab physician, lived near Cordoba in Spain. His famous 30-volume work, *Kitab al-Tasrif*, covers a broad range of medical topics, with the 28th volume *addressing pharmacy* and pharmaceutical techniques. It provides recipes and explains how to prepare the "simples" (individual plants, minerals or animal products) for compounding complex drugs in the form of ointments, syrup, powder, or tablets. In the 11th century the great Arab physician Avicenna (Ibn Sina), wrote two famous books: *Kitab al-Shifa* (Book of Healing) and *Qanun-fi-Tibb* (Canon of Medicine). The latter was translated into Latin in the 12th century and served as an authoritative text in European medical schools until the 17th century. The 5-volume book on healing—*Canon of Medicine*—emphasized the influence of environmental factors of humidity and temperature on physical ailments. Volume II of the book contains a list of 760 drugs derived from plants, chemical elements, and minerals for treatment of various diseases and, in Volume IV, Avicenna outlined his contagion theory and mentioned that people can transmit disease to others by breath and discussed the spread of disease through water and soil (Byrne, 2012). A detailed account of ancient insights into geology and health is available in Hasan et al. (2013).

Despite its critical role in human health and wellbeing, full significance of geological factors in ecological health was not recognized until recently. However, ancient scholars and practitioners of medicine were cognizant of this relationship. Indeed, as far back as 2500 years ago, Hippocrates (~400 BC) in his treatise, *On Airs*, *Waters and Places*, had emphasized the influence of physical environment on human health:

> "If you want to learn about the health of a population, look at the air they breathe, the water they drink, and the places where they live".

His text was probably the first to recognize unhealthy features of marshes, which are known to be breeding grounds for water-borne diseases, such as malaria. Elaborating on water quality, he described bad waters as:

> "Such waters then as are marshy, stagnant, and belong to lakes, are necessarily hot in summer, thick, and have strong smell, since they have no current; but being constantly supplied by rain-water... Such waters I reckon bad for every purpose."

Later Galen (129–210/216 AD) a Greek physician, surgeon, and philosopher in the Roman Empire, reiterated this aspect:

> "...they say the physician must be acquainted with air, waters, localities, occupation, food, drink and customs so that he may... discover causes of all diseases."

Historical Evolution

Students of medical geology in recent decades have been faced with confusing terminologies used for this emerging field. In order to clarify the confusion and to comprehend the relationship between geology and health, a historical perspective is helpful.

As early as the 18th century, geographers and physicians worked together and used maps to investigate the spatial distribution and incidence of diseases to control its spread. Physicians in Europe and the United States made significant contributions to this field of geomedicine. During the early 19th century Daniel Drake, a practicing physician in Cleveland, Ohio, wrote a 2-volume treatise titled *Principal Diseases of the Interior Valley of North America*. He surmised that diseases are influenced by climate, locality, and society. Drake also emphasized the importance of rocks and soils in causing disease, establishing the link between different rocks—argillaceous and calcareous—in sickness and well-being of a population (Drake, 1854).

Pervasive influence of the *miasmatic* theory—bad air causing diseases—might be the reason for the close collaboration between earth and health scientists. Later, following John Snow's detailed investigation of cause of cholera in the Soho district of London in 1854, and acceptance of the *germ* theory, collaboration between medicine and geography gradually declined as physicians shifted their focus from the physical environment to germs as leading cause of diseases. However, recent advances in remote sensing and GIS technology have revived medical geography, facilitating surveillance of vector-causing infectious diseases, such as Ebola, dengue fever, zika, COVID-19, and other zoonotic diseases. Valuable health-related databases, such as the map series on the United States population health produced by the Centers for Disease Control (CDC), Dartmouth series of atlases on health care, and others combine medical information with GIS to present valuable interactive maps that can be used by laypersons and researchers alike.

Although the term medical geology was proposed in the 1990s, it is interesting to note that it was used by an anonymous British physician who had correctly predicted medical geology to emerge as a scientific discipline, nearly 200 years ago. Writing in the *American Journal of Science and Arts*, the physician wrote:

> "Medical Geology—At some future day, I have no doubt that we shall discover that there is such a science as medical geology, viz. that certain strata are, as foundation ground for human habitations, much more liable to be affected with certain causes of diseases than others, and we shall probably not only know the fact, but ascertain the cause and the remedy. The county of Norfolk [United Kingdom] has long been famous or infamous for the astonishing number of patients affected with the stone, nothing has hitherto been done to investigate the cause. The earth, I have long since been persuaded, contains within itself agents destined to affect future changes of the solid surface, and also of the atmosphere. The pestilence and earthquake which reigned together, for 70 years during the reign of Justinian and depopulated the fairest portion of the civilized world—were doubtless the result of certain subterranean laws which regulate its internal economy—laws known only to its creator".

(Anonymous, 1834, p. 182).

Medics as Geologists

Considering the rigor of modern medical education and the complexity of striking a balance between theoretical knowledge, clinical training, and required competency to practice medicine, it is hard to believe that about 200 years ago one could practice medicine without attending a medical school. An educated person with basic understanding of natural healing substances, such as plants and minerals, could become a physician. In fact, physicians in Europe until the late 18th century were "learned gentlemen" who had acquired effective practical skills to practice medicine. Although the first medical schools in the United States were founded in the 1760s, most doctors were practicing medicine following a 3–4 years apprenticeship with a reputed physician (Custers and Cate, 2018). Prior college education for admission into a medical school became a requirement in Europe during the last decade of the 19th century. In the United States too, until the mid-19th century, formal education at a college was not required and an extended apprenticeship was all the medical education one needed to practice medicine. In 1895, the Chicago Medical School (now part of the Northwestern University) made college education a requirement for admission into its medical school. Later, in 1898, Johns Hopkins University required all medical school applicants to have a bachelor's degree. Harvard University in 1901 also required a college degree for medical school admission.

Medical geology represents a re-emergence of a vocation that engaged the medical practitioners from the 17th until the mid-19th century. As was common in this period, medical education required theoretical studies comprising Latin and three main disciplines: religion, law, and natural science, the later included philosophy, geology, mineralogy, and botany. Many physicians found geology intellectually more stimulating and shifted their interest and career into the field of geology to become famous geologists. A partial list of famous geologists who were initially trained as physicians is presented in Table 1.

Re-Emergence of Medical Geology

The term *geomedicine*, which has been extensively used by many researchers, notably J. Lag of the Geological Survey of Norway (NGU) who edited a major book on the subject (Lag, 1990), was one of the two names considered for the emerging subspecialty. But it did not find favor because geomedicine connotes a subspecialty of medicine, such as family medicine, nuclear medicine, etc.

Table 1 Famous geologists trained as physicians.

Name	*Period*	*Country*	*Geologic contribution*
1. James Hutton, MD	1726–1797	United Kingdom	Received his MD in 1749, wrote a thesis titled On the Circulation of the Blood. Practiced medicine briefly then took up farming in the Scottish Highlands, studying the geology of the region. Wrote *The Theory of the Earth* in 1795, laying down the basic principles of geology.
2. William Babington, MD	1756–1833	United Kingdom	Received his MD in 1795. Authored A New System of Mineralogy (1799). Was instrumental in founding of the Geological Society of London in 1807, served as its President (1822–24).
3. William Hyde Wollaston, MD	1766–1828	United Kingdom	Worked as a physician for a short time, devoting his time to research in mineralogy and chemistry. Invented a method to prepare pure Pt; discoverer of the elements Pd and Rh. Served as President of the Royal Society of London (1820). The Wollaston Medal, the highest award in geology is awarded annually by the Geological Society of London in his honor.
4. John Jeremiah Bigsby, MD	1792–1881	United Kingdom	Studied geology of the St. Lawrence valley to western edge of Lake Superior; published many papers. Established the Bigsby Medal at the London Geological Society for distinguished work in geology to someone not older than 45 years. Member of the American Geological Society (1810).
5. James Parkinson, MD	1755–1824	United Kingdom	Physician and paleontologist; wrote 3-volume book *Organic remains of a former world.* Founding member of the Geological Society of London. (Parkinson's disease is named after him, though he did not suffer from it).
6. Gerard Troost, MD	1776–1850	United States	State geologist of Tennessee (1831–47); professor of chemistry, geology, and mineralogy, University of Nashville; President, Academy of Natural Sciences.
7. Benjamin Silliman, Sr; MD	1779–1864	United States	Professor of chemistry and geology at Yale. Silliman Professorship at Yale named after him.
8. William Byrd Powell, MD	1799–1867	United States	State geologist of Arkansas. Professor of Medical Geology in Kentucky.
9. Robert Peter, MD	1805–1894	United States	Professor of chemistry at Kentucky Medical School. Wrote *Relations of forms of disease to geological formations of region.*
10. Henry King, MD	1805–1863?	United States	Carried out extensive geological work in Missouri; Geological member of the AAAS (1848–54).
11. Louis (J.L.R.) Agassiz, MD	1807–1873	United States	Founder of the Glacial Age theory; professor of Geology at Harvard.
12. Ferdinand Vandevere Hayden, MD	1829–1887	United States	Great explorer of the U.S. Geological Survey. Professor of geology and mineralogy, University of Pennsylvania.

So, the term medical geology, first mentioned in 1834 by an anonymous British physician (see quotation above), was officially adopted about 163 years later in 1997 at a meeting of the medical geology working group at the 4th International Symposium on Environmental Geochemistry held at Vail, Colorado, United States. Professor O. Selinus, as a member of The Commission on Geological Sciences for Environmental Planning (COGEOENVIRONMENT) of the International Union of Geosciences (IUGS), had earlier (in 1996) suggested the idea of forming a working group on medical geology. IUGS accepted the proposal and appointed Selinus chair of the working group. The working group at Vail officially adopted the title Medical Geology at a meeting with several geoscientists, public health professionals, and medical scientists. It was fully agreed that the term geomedicine was not the appropriate name to describe this discipline as the name was not considered by the medical and public health communities to be applicable and relevant to their profession (Selinus, 2019, 2020).

Medical Geology Definition

The International Medical Geology Association (IMGA) defines medical geology as... "the science dealing with the relationship between geological factors and health problems in humans, animals and plants". This is a broad definition that is somewhat restrictive in the sense that it does not mention the non-living components of the environment, such as, air, water, and soil, which are all very important in health and disease. A more inclusive definition was proposed by Bunnell, who defined medical geology as a .....“scientific discipline that examines the impacts that geologic materials and processes have on human and ecosystem health...” and added that .....“includes both natural and anthropogenic sources of potential health problems...” (Bunnell, 2004). Cognizant of the need to emphasize global climate change and its far-reaching consequences on human and ecosystem health, and the important role of medical geology in minimizing its adverse impacts on public health and ecosystem protection, a slight modification was subsequently proposed that defined medical geology as ....“the science that deals with the influence of anthropogenic and geological factors on human and ecological health” (Hasan, 2019).

Scope of Medical Geology

Modern medical geology represents a multidisciplinary science, that intersects the earth, health, and life sciences. It covers a wide range of chemical, biological, and physical environments at scales extending from the microscopic (e.g., involving studies of individual microbes or chemicals in tissue samples) to global (e.g., examining the provenance of atmosphere-borne particulate materials and pathogens transported by intercontinental dust storms). Challenging and exciting new areas are unfolding every day, offering infinite opportunities for medical geologists to make valuable contributions for safeguarding human and ecological health. For example, control of geologic factors on (i) the prevalence of cardiovascular and Alzheimer's disease, neurological disorders from imbalance of trace elements; (ii) antibiotic properties of clay minerals; (iii) lithium levels in drinking water and tendency for suicide; (iv) surveillance and mitigation of zoonotic and other diseases triggered by climate change; and (v) control of pollution related mortality and morbidity. An expanding role for medical geologists in effective management of global health is also envisioned in multidisciplinary teams and committees charged with information dissemination, citizen science, public education, and policy making.

Geological Materials and Processes

Chemical elements and compounds derived from geological materials and processes influence the quality of water and availability of major and minor chemical elements (nutrients) in soil to support plant life and sustain agriculture. Hazardous geological processes, such as floods, landslides, earthquakes and volcanic activities mobilize chemical elements and compounds into the environment that can produce both beneficial and harmful impacts on all life forms. Geology, in other words, plays a key role in health and wellbeing of humans, plants, and animals.

All naturally-occurring chemical elements are derived from rocks. The topmost layer of the Earth, called crust, is a relatively thin (5–40 km) layer of rigid, brittle rocks that is exposed to the atmosphere. Depending on the location at the Earth's surface and climate, rocks of the crust are being continuously subjected to a series of complex physical, chemical and biochemical reactions termed *weathering*. This interaction results in breakdown of rocks into discrete mineral grains, with accompanying release of various elements and compounds into the environment. Geologic processes involving action of wind, water, and ice carry the elements and compounds released during the weathering process from one location to the other. The processes of erosion, transportation, and deposition result in accumulation of geologic materials at a new location. It also results in excess or deficiency of chemical elements and compounds at various locations on the Earth, both of which are critical from a health perspective (see section "Chemical Elements and Health" for details).

Other large-scale geologic processes, such as volcanic eruptions, can release huge quantities of harmful solids, toxic acids, gases, and aerosols into the atmosphere without any warning, exposing people to dangerous and, often deadly, substances. The Laki volcano in Iceland, which erupted intermittently for 8 months between June 1783 and February 1784 is estimated to have introduced 120 metric tons (MT) of SO_2, 15.1 MT of HF, and 6.8 MT of HCl into the atmosphere. These acidic materials brought large scale destruction, including 10,000 deaths resulting from the "haze famine" caused by the persistent presence of toxic acids that caused large-scale damage to crops, and massive livestock loss, wiping out 50% of all island cattle and horses, and 80% of the sheep. Similarly, the June 1991 eruption of Mt. Pinatubo in the Philippines released 20 million MT of SO_2, 800,00 MT of Zn, 600,000 MT of Cu, 550,00 MT of Cr, 100,000 MT of Pb, 30,000 MT of Ni, 10,000 MT of As, 1000 MT of Cd, and 800 MT of Hg. Some of these heavy metals and gases are highly toxic and capable of causing serious health problems, including cancer.

The global stratospheric circulation, known as the "Jet Stream," transports large quantities of dust particles, often containing pathogens, 1000s of kilometers across continents and oceans, exposing distant populations to harmful and toxic substances. Strong earthquakes of M 5.0 or more result in collapse of building and structures, generating fine dust-like materials loaded with a variety of harmful substances. Fine particles can remain suspended in the air for considerable period of time to enter into living organisms, including humans, through inhalation and/or ingestion. Cases of physical injuries and deaths associated with earthquakes have been widely reported, but health problems are also caused by inhalation of dust. An interesting example is the high incidence of coccidioidomycosis (or valley fever) following the 17th January 1994, M 6.7 Northridge earthquake in southern California. The major and after-shocks triggered over 11,000 landslides that whipped up the soil and caused the arthrospores to be plucked and attach to fine dust. The prevailing northwesterly winds dispersed large dust clouds into nearby valleys. Inhalation of dust carrying the spores *Coccidioides immitis* and *C. posadasii* of the fungus *Coccidioides* resulted in a higher incidence of coccidioidomycosis in Simi valley in Ventura County. Between January 24 and March 15, 1994, 203 outbreaks of coccidioidomycosis cases, including three fatalities, were reported in the area (Schneider, et al., 1997).

Rocks and Minerals

Geologic materials, especially minerals, have been used for therapeutic purposes for several millennia in various cultures. Lithotherapy was practiced until the 16th century, but was phased out when a more empirical approach, following the Paracelsian revolution, was embraced in pharmacology. Paracelsus (1493–1541), unlike Galen, believed that three humors—salt, sulfur, and mercury, in right proportions, were essential for health, and separation of one humor from the other two caused disease. By contrast, Galen believed that good health resulted as long as the four humors in the body—blood, phlegm, black, and yellow bile—remained in balance, and the preponderance of one over the others resulted in sickness.

Among the metals, arsenic, copper, gold, mercury, and sliver were commonly used for treatment of various ailments. Despite their toxic nature, arsenic, copper, and mercury, in the right combination with herbs and other substances found many applications in ancient medicinal practices. Gold particularly was widely used in Arabic medicine and Avicenna used gold filings for treatment of bad breath, hair loss, depression, heart health, and as a cauterizing agent for wounds. In Europe, it was used for treatment of syncope, lassitude, and other problems. One of the popular formulations, *Aurum potabile*—a fine suspension of gold, mixed with other ingredients in a suitable drinking fluid, was used to treat paralysis and cardiac conditions.

Pumice, as a geopharmaceutical material, has been used in ancient Arabic, Chinese, Greek, and Western medicine as a medical abrasive, dentifrice, depilatory agent, and for cauterization.

Some minerals, such as alum [$KAl(SO_4)_2 . 12H_2O$], clay, borax ($Na_2B_4O_7 . 10H_2O$), marble ($CaCO_3$), nacre (mother of pearl, aragonite, $CaCO_3$), lapis lazuli [$Na_3Ca(Si_3Al_3)O_{12}S$], lime (CaO), marcasite (FeS_2), orpiment (As_2S_3), common salt ($NaCl$), sulfur, and vitriol (various sulfates, e.g., red vitriol, $CoSO_4$; white vitriol, $ZnSO_4$; blue vitriol, $CuSO_4$) continued to be used in medicinal formulation with much success. Some natural geologic materials are used even now in many health care products (Fig. 1). Recently a dehydrated Cuban zeolite paste, called Detoxsan, has been effectively used for treatment of skin diseases such as mycosis and intertrigo (Torres et al., 2019).

One of the interesting uses of geologic materials includes *gem* electuary—use of crushed precious stones mixed with herbs and animal products, such as coral, ivory, musk, and pearl in the form of a paste, for oral or topical application to treat a variety of health problems. Amber, chalcedony, emerald, garnet, and sapphire were common *gem*s that had been used to treat symptoms ranging from nightmares, to gynecological, gastrointestinal, and even plague. The high cost of gem electuary limited it to royalty and rich people. After enjoying popularity for about 400 years, this practice was abandoned in the early 18th century (Duffin, 2012, pp. 81–111).

Clays in healing

Clays have been used in healing for over 2000 years, and are used in healthcare products even today. *Terra sigillata*, or "sealed earths," from Greek islands, Malta, Palestine, Armenia, Turkey, and central Europe were used to cure several maladies, notably poisoning. It was used extensively from the 13th to 16th centuries and was mentioned in all medical books until the 18th century. Its claimed medical benefits were considered to be associated with faith and superstition. However, recent studies have shown that the high cation exchange capacity of certain clay minerals, such as montmorillonite, that is known to take up harmful toxic heavy metal ions (e.g., As, Hg), may account for use of montmorillonite-rich samples of *terra sigillata* as an antidote for poisoning. High absorbency of toxic molecules by kaolin and other clay minerals could also explain use of certain *terra sigillata* for effective treatment of gastrointestinal problems, particularly gastroenteritis.

Geophagy

Geophagy, also known as geophagia, is intentional ingestion of earthy substances. Pica is a medical term used to characterize craving and consumption of non-food substances, such as, soil, clay (geophagy), raw starch (amylophagy), and ice (papophagy). Geophagia was reported about 2500 years ago by Hippocrates and is being practiced in many countries even today,

Fig. 1 Common health care products formulated from minerals.

but is most common in warm tropical countries. A study by Young et al. (2011) analyzed cases of geophagia in various countries and found that: (i) in East African countries (Tanzania, Kenya, Malawi, Uganda) between 30% and 60% of pregnant women reported eating soil; (ii) in a cold country like Denmark, 0.01% pregnant women reported eating soil; and (iii) in the United States between 20% and 40% of low-income pregnant women in southern Mississippi State reported craving for dirt, ice, starch, or ash.

Various hypotheses have been proposed to explain the effectiveness of geophagy. One of the more plausible hypotheses is the protection provided by ingested clay against infectious agents by forming a protective layer that protects the stomach against parasites, pathogens, and toxic substances. According to Young et al. (2011), geophagy is most commonly practiced by women in early stages of pregnancy and in pre-adolescent children who are most sensitive to parasites and pathogens. Recently, Londono et al. (2017) investigated the antibacterial activities of an alluvial clay from the Amazon in Colombia. They concluded that Al toxicity plays a central role in the antibacterial action of kaolin—an Al-rich clay—by damaging the cell membrane, making it more permeable to intracellular transport of toxic metals that kill the pathogens.

Geophagy in animals

Accidental, or involuntary soil ingestion is common in both domesticated and wild animals. Grazing animals ingest soil adhering to vegetation, or directly from the ground surface. Geophagy has been observed in vertebrate herbivorous animals in *Reptilia* (iguana, box turtle, tortoise); *Aves* (ostrich, goose, vulture, dove, pigeon, parrot, starling, sparrow, canary, bunting and other birds); and *Mammalia* (rabbit, squirrel, elephant, horse, ass, zebra, black rhino, camel, caribou, deer, sambar, giraffe, antelope, sheep, goat, buffalo, ox, baboon, langur, chimpanzee, gorilla, etc.). Among non-vertebrates, butterflies and isopods also deliberately consume soil. Geophagy has not been reported in carnivores.

Soil ingestion by animals is selective in terms of location and soil type; and specific sites are called *lick*. The size of a lick ranges from small scrapes to very large, from 2000 to 55,000 m^2, with holes and caves excavated by elephants using their tusks, trunks, and front legs. Lick soils are characterized by high content of clay-size particles, high salinity, and high $CaCO_3$ with or without $MgCO_3$ (Abrahams, 2013).

A well-documented study of geophagy in baboons (*Papio cynocephalus ursinus*) was carried out by Pebsworth et al. (2011) in the Wildcliff Nature Reserve in South Africa. After monitoring the pattern of soil consumption continuously for 18 months, it was observed that pregnant baboons consumed more soil than non-pregnant females, males, or juveniles. All preferred alkaline silty clay (pH 9.4–9.8) with a high concentration of Na (500–1140 ppm) and low Fe (1.1–6.17 ppm), over acidic soil (pH 4.6). Mineral content of the soils consumed was (in decreasing order) quartz, illite, kaolinite, gibbsite, paragonite, siderite, halite, and magnesite, with some smectites. The study confirmed that consumption of soil provided protection to baboons against gastrointestinal diseases and from dietary toxins and pathogens.

Dust and Air Pollution

Aerosols are suspensions of microscopic size solids, or tiny droplets of liquid, or gas in the air. Fine atmospheric dust, comprising mineral grains, mineral fibers, organic and inorganic materials, and pathogens are readily entrained and circulated by prevailing air flows. Such suspensions are known to travel across continents. Upon deposition, the harmful materials can cause a variety of health problems, dominated by respiratory tract ailments. Suspended materials also impair air quality, manifested by poor visibility, haze, and fog. Besides increased health care cost, dust and air pollution also take a heavy economic toll from reduced agricultural productivity, loss of fishery resources in dust-contaminated water bodies, higher and recurring cost of maintaining highways, and disruption of airline passenger and transport services.

Aerosol inhalation affects millions of people in the mid-latitude arid region between the Yellow Sea and the Mediterranean Sea (Derbyshire, 2013). Some common diseases associated with aerosol inhalation include: pneumoconiosis, asbestosis, and tuberculosis. Miners and other construction workers, working for extended periods of time with limited or no protection are known to develop silicosis and mesothelioma due to prolonged inhalation of silica dust and asbestos fibers.

Huge quantities of desert dust, up to an estimated 5.0 billion tons, move through the atmosphere each year. The larger deserts on the planet, which include the Sahara of North Africa; and the Gobi, Takla Makan, and Badain Jaran deserts in China, are the primary sources of mobilized desert soils that move great distances through the atmosphere each year across the globe. Dust storm activities are also common in arid regions of southwest United States, Central America, South America, Central Australia, South Africa, and the Middle East. Dust storms emanating from the Sahel region of Africa can reach the Caribbean and Americas within 3–5 days. Asian dust storms can take from 7 to 9 days to cross the Pacific Ocean. Dust storms occur in North Africa throughout the year, but dust storm activity in the deserts of Asia is seasonal-majority occurring during February to May.

Inhalation and ingestion are common pathways for entry of aerosols into human body. The number of ultrafine particles (<100 nm) that accumulate in the lungs increases with decreasing particle size. Elderly people, young children, and individuals with chronic cardiopulmonary diseases are the most vulnerable segment of population. Increased inhalation of particulate materials has recently been found to increase ear infection in children. Acute *otitis media* is one of the most common ear infections affecting preschool age children in the United States and costs between 3 and 5 billion dollars annually (Ahmed et al., 2013). Fine particles, <2.5 μm, can also penetrate deep inside the lung to cause a variety of dust-related infectious diseases including influenza A, pulmonary coccidioidomycosis, bacterial pneumonia, and meningococcal meningitis. Non-infectious diseases, chronic obstructive pulmonary disease (COPD), asthma, sarcoidosis and pulmonary fibrosis are also linked to particulate materials, N_2, and other air pollutants.

Fine particulate materials up to 10 μm in size, come from both natural and anthropogenic sources. Volcanic eruption (tephra), loose geologic materials such as alluvial deposits, glacial outwash accumulations, loess, and weathered rocks, are some of the common natural sources. Industrial emissions, biomass burning (produces carbon black), explosives used to excavate hard foundation materials, military operations involving powerful bombs, and terrorist activities also generate dusts loaded with harmful substances. Studies undertaken by the U.S. Geological Survey (USGS) on the nature and extent of dust generated following the September 11, 2001 attack on New York's World Trade Center observed that slag wool (a man-made vitreous fiber), gypsum ($CaSO_4 . 2H_2O$), anhydrite ($CaSO_4$), and phases compatible with concrete, metal or metal oxides, mineral material, and asbestos in trace to minor amounts were present in residences, public buildings, and office spaces across New York City (USGS, 2005).

Dust clouds also carry biological substances, such as fungal spores, bacteria, viruses, and pollen, etc. Dust-borne microorganisms can lead to allergic reactions and asthma upon prolonged exposure. Incidence of pneumonia in populations exposed to dust storms has been reported throughout the course of time. During the American Dust Bowl of the 1930s, the numbers of cases of pneumonia increased significantly. In recent decades, pneumonia from dust storm exposure has also been reported in the Middle East among the deployed military personnel. Pneumonia acquired from exposure to inorganic and organic materials in dust storms has been termed *Al Eskan* disease, Persian Gulf syndrome, Persian Gulf War syndrome, Gulf War syndrome, or desert dust pneumonitis.

Chemical Elements and Health

All living beings depend upon essential elements or nutrients for their survival. Nutrients are derived from the rocks of the earth and are present in air, water, and soil; they comprise Periodic Table of elements (Fig. 2); they could be in the elemental form, such as O, Fe, Ca, Na, K, Mg or chemical compounds, such as H_2O, NaCl, etc. While some nutrients are readily available in air and water and are taken in directly, nutrients that originate from rocks occurring on the earth, need to be in a specific chemical form that can be absorbed in the body. The mere presence of chemical elements or compounds is not the only requirement for uptake by living forms: it has to be bioavailable. In other words, it must be in a form that can be assimilated by living cells. For example, elemental nitrogen (N) comprises 78% of the air that we breathe, but in order for N to serve as a nutrient to plants it must be in a bioavailable form, such as NO_3, NH_4, etc.

Essential, Major, Minor, and Trace Elements

Major elements include the 11 chemical elements that are necessary for life; for this reason, they are called "essential elements." These elements include: H, O, C, N, Na, K, Ca, Mg, P, S, and Cl. These 11 elements comprise 99.9% of the human body; and four of

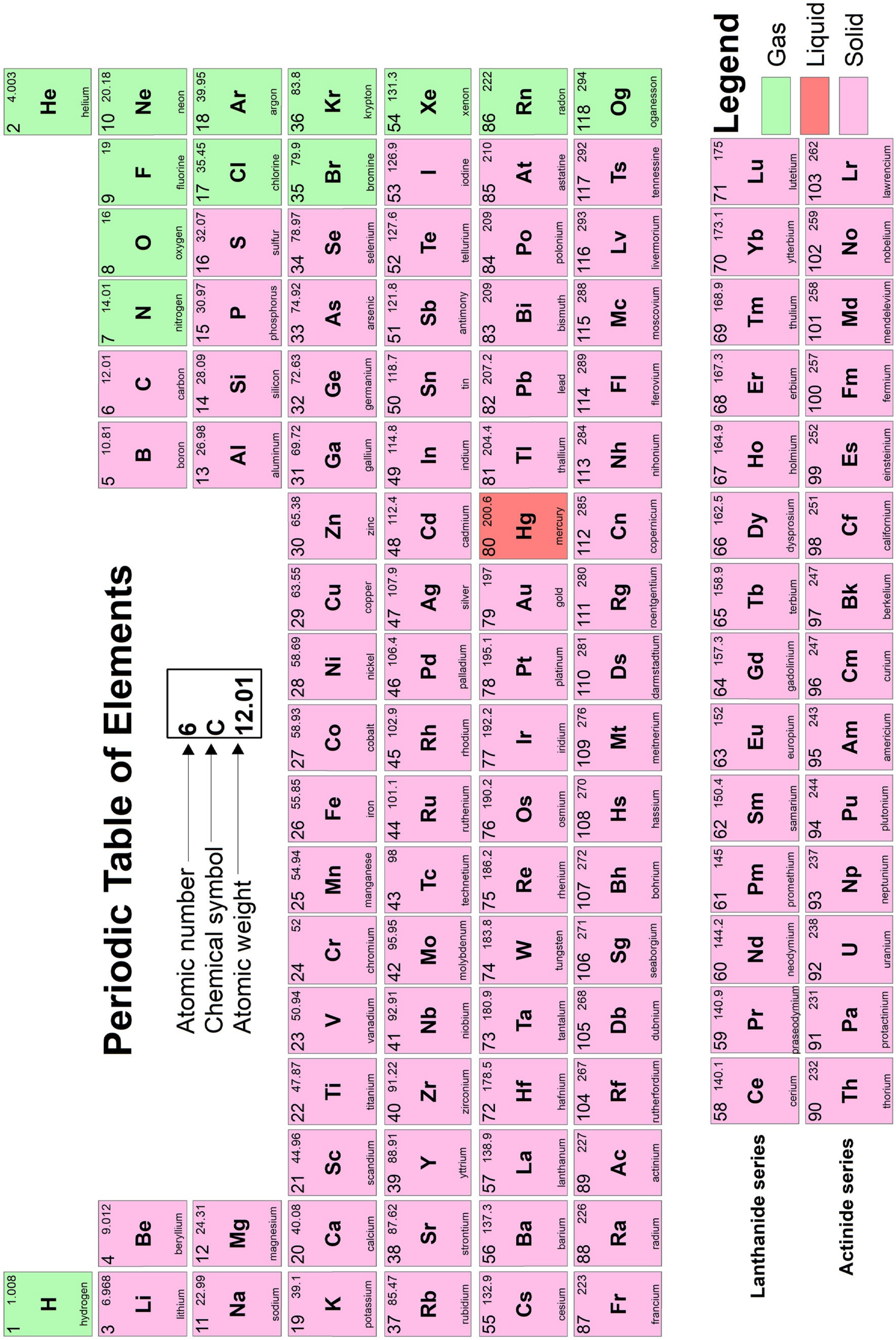

Fig. 2 Periodic table of elements.

these—O, C, H, and N, that make up 99% of the human body, are called major elements. The remaining seven, Ca, P, Mg, K, S, Na, and Cl, comprise <1% of human body and are called minor elements. In addition, a number of other elements occur in minute or trace quantities in the human body and are called trace elements. Trace elements include: Si, Fe, Zn, F, Cu, Br, As, Sn, I, Mn, Mo, Ni, Se, Va, Cr, Co, Li, and W. Table 2 lists the major, minor, and trace elements present in the human body.

As shown in Table 2, major elements occur in large quantities, 1000s of g or more and make up the bulk (99%) of the human body. Minor elements occur in small quantities, <1 g (ppm range); while trace elements comprise tiny amounts, <0.1 g (ppm-ppb range).

Minor or Trace Elements

Despite occurring in minute quantities in the human body and other organisms, trace elements perform a vital role in maintaining health and well-being. However, a unique aspect of trace elements is that they must be present in small and well-regulated amounts to be beneficial. If the quantity is below or above the optimum range an element can become harmful; for most trace elements there is a narrow range of concentration within which the benefit to the organism is realized. This concept can be best illustrated by the dose-response curve that displays the relationship between varying concentration (dose) of trace element and health outcome to the organism.

As can be seen in Fig. 3, very low or zero concentration as well as high concentrations of trace element are harmful and there is a certain range of dose where it produces maximum benefit to the organism (see "Fluorine and Dental Health" section).

Two well-known examples of adding trace elements to prevent disease include use of iodine in table salt and fluorine in public drinking water supplies. Use of iodine to control goiter dates back to ancient times. Around 3500 BC, Chinese healing included ingestion of seaweed and burnt sea sponge for reducing goiter size. The remedies remained effective and their use continued globally for millennia; but discovery of the element iodine in 1813 replaced the need for seaweeds and sponge.

Table 2 Chemical elements in human body and their classification.

Class	*Elements*	*Concentration*
Essential elements	H, O, C, Ca, Mg, N, Na, K, Mg, P, S	Comprise 99.9% of human body
Major elements	C, H, N, O	>1%, comprise 3–65% of human body
Minor elements	Ca, Cl, K, Mg, Na, P, S	0.1–1% (1000–10,000 ppm)
Trace elements	As, Br, Co, Cr, Cu, F, Fe, I, Li, Mn, Mo, Ni, Se, V, W, Zn	<0.1%

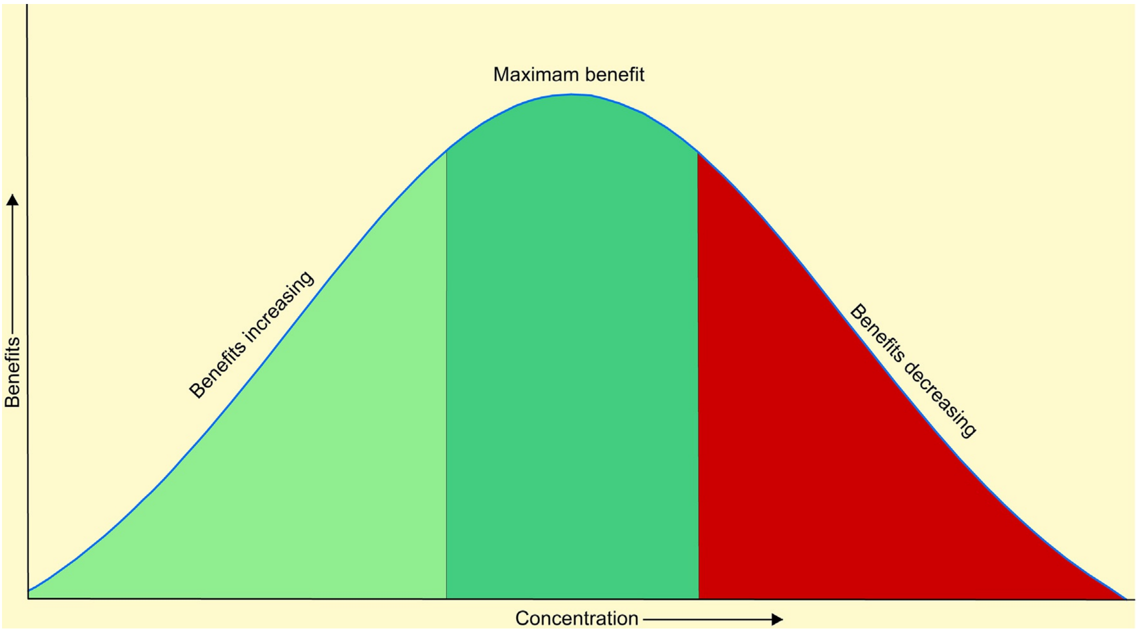

Fig. 3 Generalized dose-response curve.

Adequate levels of iodine, a trace element occurring in a concentration range of 0.2–1.9 mg/kg in rocks, is found mostly in soil and water of coastal areas. Iodine is important for synthesis of thyroid hormones that play key roles in the metabolic processes of vertebrates. Major health impacts from a global burden of iodine deficiency are related to goiter, neurocognitive impairments, and in the case of severe deficiency, hypothyroidism, resulting in cretinism (a congenital condition caused by deficiency of thyroid hormone during prenatal development and characterized by retarded mental and physical development, and dystrophy of bones).

Iodization of salt has been very successful in reducing iodine deficiency in populations, because salt is a universal food item, intake is consistent, and is inexpensive. The U.S. was historically iodine deficient prior to the early 1920s, particularly in the goiter belt region of the Great Lakes, Appalachians, and the northwestern area of the country where 26–70% of children showed clinical symptoms of goiter. Following the successful implementation of a salt iodization program in Switzerland, introduction of iodized table salt in the U.S. during the 1920s significantly improved the nutritional deficiency of iodine. Salt iodization has now been adopted by nearly 120 countries. Table salt containing 150 μg/L of iodine prevents thyroid related diseases. This small quantity is equivalent to one table spoon of iodine consumed by a person in his life time. Despite the simple remedy, iodine deficiency remains one of the most significant public health issues globally, with an estimated 2.2 billion people living in iodine-deficient areas.

The fluorine concentration in natural water varies over some four orders of magnitude, from 0.1 to 10 ppm. Fluoride levels between 0.5 and 1.5 ppm in drinking water are beneficial, promoting dental health and preventing tooth decay. High concentrations (1.5–4 ppm) of fluoride in drinking water cause mottling of teeth (dental fluorosis) and higher levels (4 ppm and above) result in skeletal fluorosis, which causes hardening and calcification of bones, pain, and bone deformation. At the same time, complete absence or very low concentration (0.00–0.5 ppm) causes dental caries.

The first attempt to regulate drinking water supply in the U.S. occurred in the mid-1940s following studies by the U.S. Public Health Service that set the upper limit for fluoride in drinking water at 1.0 ppm, later increasing the amount to 1.5 ppm. Subsequently, the US Environmental Protection Agency, under the Clean Water Act of 1972 raised the maximum enforceable fluoride concentration to 4.0 ppm. The World Health Organization (WHO) guideline value for fluoride is set at 1.5 ppm, which has been adopted by Canada, China, European Union, India, and many other countries.

Fluoride concentration in drinking water is adjusted in municipal drinking water supply systems at 0.7 ppm to ensure that its concentration will not exceed 4.0 ppm in communities where fluoride is present in natural water. Fluoridation of drinking water is done by adding either fluorosilicic acid (also referred to as FSA) or hydrofluoro silicate, sodium fluorosilicate, or sodium fluoride. FSA is the most common additive and has been used in the U.S. drinking water systems since the early 1950s. As of 2016, about 73% of the U.S. population had access to fluoridated drinking water.

Trace Elements: Excess Versus Deficiency

Paracelsus in the 16th century formulated a basic principle of toxicology stating: . . .. "All things are poison, and nothing is without poison, the dosage alone makes it so...", which means that a substance can produce harmful effect associated with its toxic properties only if it reaches a susceptible biological system in a sufficiently high concentration. This principle relies on the finding that all chemicals, even water and life-supporting oxygen, can be toxic if too much is consumed. Trace elements provide best example to illustrate this maxim. For a long time, the response to toxic substances on living organisms was studied in the laboratory on test animals, typically mice, and rabbits, but other species such as minnows, and even monkeys, have also been used to determine the optimum doses of chemicals. This is a very slow, inhumane, and extremely expensive process that has deterred testing of thousands of chemicals that are in everyday use. However, recent advances in robotics technology aided by high power computation led to the establishment of *Tox21*, in 2008, a collaborative program between three U.S. federal agencies: the Environmental Protection Agency, National Center for Advancing Translational Sciences, and the Food and Drug Administration. *Tox21* is capable of testing a chemical or biological substance at various concentrations and evaluating its effect on living cells very rapidly. Over a million chemicals can be tested at concentration levels spreading over four orders of magnitude. *Tox21* holds the promise to rapidly test the multitude of commercial chemicals whose toxicity is poorly understood. Refinements in testing procedures are being made continuously and updates of the *Tox21* program are available on-line at: https://tox21.gov/. In addition, detailed information on the health impacts of toxic substances is available at the website maintained by the Agency for Toxic Substances & Disease Registry (ATSDR): https://www.atsdr.cdc.gov/substances/index.asp.

Trace Element Research

The last four decades of the 20th century witnessed an unprecedented advance in science and technology, which brought about the digital revolution. During this time, the capability to probe, detect, and analyze almost any material to a high level of precision took a quantum leap forward. Sophisticated analytical equipment, supported by powerful computers enables the analysis of geological materials rapidly at a high level of precision and accuracy. Detection of chemical elements and compounds in environmental samples to sub-ppm levels has become routine procedure in modern analytical laboratories. This development has led to an enhanced interest in understanding the geochemistry of the natural environment and initiation of ambitious projects to prepare geochemical atlases at local, state, regional, and national levels in the European Union, the United States, China, and many other countries. These geochemical surveys that commenced in the 1960s are still continuing. Information on occurrence, distribution, and concentration of chemical elements in soil, sediment, water, and plants has been used for a variety of applications, such as agriculture, environmental pollution, fisheries, medicine, public health, water supply, wildlife nutrition, and other areas (Thornton, 1993). The pioneering work done by the national geological surveys of Sweden, the United Kingdom, and the United States on the influence of trace elements on health between the 1960s and 1980s laid the foundation for focused studies on the relationship between geological materials and processes on human health. It should be noted that similar studies on animals and plants had been carried out much earlier by animal and plant scientists, who investigated the association of essential and trace elements on diseases in animals and plants. Despite the numerous studies linking chemical elements and compounds on occurrence of disease in human beings, such studies remained as isolated investigations in geochemistry and epidemiology. However, an interdisciplinary symposium held in Montreal, Canada, at the 1964 meeting of the American Association for the Advancement of Science (AAAS), organized by its Geology and Geography sections, and the Geochemical Society, provided a major impetus for recognizing the importance of geological factors in human health. The landmark publication *Environmental Geochemistry in Health and Disease* (Cannon and Hopps, 1971) by the Geological Society of America was seminal in this context. At the same time, various initiatives in Europe by the British, Finnish, and Swedish geological surveys served as the needed catalyst for establishment of a new subspecialty within the earth sciences.

The USGS has been playing a key role in research and dissemination of information relating to trace element impacts on human and animal health for the past 75 years. Its Contaminant Biology Program (CBP) that started in the 1940s has focused on the effects of contaminants in fish and other wildlife. Growing pollution and deterioration in the nation's water quality during the 1960s to 1980s led to the establishment in 1982 of the Toxic Hydrology Program (THP). These two programs were merged into the Environmental Health Mission Area in 2010, whose objective is to assess and advise the nation about risks to the environment from contaminants and pathogens. The program investigates contaminant and pathogen sources, transport, exposure, pathways, uptake, biological effects, and human health implications. Its electronic newsletter *GeoHealth*, now in its 19th year of publication (the initial issue, called *Epidemiology News*, was published in May 2002 and later renamed *GeoHealth* in 2004), contains information on the latest researches in environmental health that are timely and offer useful information to citizens, students, and professionals in medical geology.

Among the academic institutions, the University of Missouri-Columbia (UMC) must be credited for its farsighted vision to establish the Environmental Trace Substances Center (ETSC) devoted to the study of trace substances in environmental health. Professor Delbert Hemphill and his colleagues at UMC convened the first conference on trace substances in 1967, that was subsequently organized and managed by the ETSC. In all, 25 annual conferences were held, covering a variety of topics on the role of trace substances in human and ecological health. Its proceedings volume contains a wealth of information on trace substances and their impact on human and ecological health. The Society for Environmental Geochemistry and Health (SEGH) that was formed in Dallas, Texas in December 1968 at the symposium on "Environmental Geochemistry in Health and Disease" collaborated with the ETSC and held its first annual meeting in 1970 during the "3rd Annual Conference on Trace Substances in Environmental Health" at UMC. SEGH continued to hold its annual meetings at UMC until 1993 when the ETSC closed and the conference series ended. The symbiotic relation between these two organizations attracted all well-known researchers in the field from the world over, and the conference proceedings still serve as a valuable resource to students and professionals alike. Many of the SEGH members and officers served on the U.S. National Research Academy's Subcommittee on the Geochemical Environment in Relation to Health and Disease created under the U.S. National Committee for Geochemistry, a Division of Earth Sciences of the National Research Council, when it was established in 1969. The subcommittee published three reports on Geochemistry and the Environment in 1972, '73, and '74 and other valuable documents that included reports on: (i) the geochemistry of water in relation to cardiovascular disease, (ii) the trace-element geochemistry of coal resources development related to environmental quality and health, (iii) aging and the geochemical environment, and (iv) geochemical environment and urolithiasis (kidney stones), all topics highly relevant to medical geology. It may be stated that the contributions made by scientists associated with these two organizations, and others in Europe, provided the stimulus and set the course for modern medical geology.

Water Quality and Cardiovascular Disease

In an early study, Schroeder (1960) observed that mortality from cardiovascular diseases (CVD) in the United States does not relate to dietary, racial, or social factors, but to drinking water quality. Statistical analyses of water hardness and death rates from CVD showed a highly significant correlation. Of the 21 constituents of finished municipal water, highly significant correlations were found for magnesium, calcium, bicarbonate, sulfate, fluoride, dissolved solids, specific conductance, and pH. In general, hard water caused lower deaths from CVD, while soft water was associated with higher death rates.

Another study by Bain (1979) in the US state of Ohio observed that higher death rates from CVD were associated with soft water. It was found that soft water occurs in counties in the southeastern part of the state, which is due to high sulfate concentration in the coal-bearing formations of Pennsylvanian to Permian age (318–251 million years). In contrast, water supply in the western part of the state is derived from the younger Wisconsin age (75,000–11,000 years) glacial deposits that have high bicarbonate concentrations. A review of death from CVD for the period 1968–71 showed that more deaths occurred in areas with high sulfate levels and less deaths with high bicarbonate concentration.

A more recent study by Catling et al. (2008) based on meta-analysis of case control studies, found significant evidence of an inverse correlation between magnesium levels in drinking water and cardiovascular mortality. This finding explains the associations reported between total water hardness and cardiovascular mortality in earlier studies. However, the influence of other factors, such as climatological, environmental, and social, also needs to be taken into account.

Lack of a definite conclusion on the relationship between water quality and CVD highlights the need for more focused studies, and the importance of collaboration between medical geologists and health professionals.

Arsenic in Drinking Water

Arsenic (As), is the 20th most abundant element in Earth's crust and about 250 minerals are known to contain arsenic. Average As concentrations in crustal rocks range from 1.5 to 2 ppm. The inorganic forms, consisting mostly of arsenite and arsenate compounds, are toxic to human health. Human exposure to arsenic is primarily from air, food and water. Drinking water gets contaminated with arsenic from arsenical pesticides, natural mineral deposits, or improperly disposed arsenical chemicals. Elevated arsenic level in drinking water is the major cause of arsenic toxicity in the world. Arsenic contamination in near-surface water has been reported from more than 30 countries. Major regions affected are in Argentina, Bangladesh, Burkina Faso, Cambodia, Chile, China, Hungary, India, Laos, Mexico, Nepal, Romania, Spain, Taiwan, Thailand, and Vietnam. Arsenic can become mobilized into the environment, notably water, through a complex set of biogeochemical reactions and human activities, such as mining, fossil fuel combustion, and use of pesticides, herbicides, arsenic-based additives in livestock feed, and in treated wood. Wood treated with chromated copper arsenate (CCA) has been used both in residential and industrial sectors of the United States since the 1940s. Residential use was voluntarily stopped by wood manufacturers beginning January 2004. Similar restrictions are also in place within the European Union.

Human exposure to arsenic occurs through ingestion and inhalation, mainly from drinking water contaminated with arsenic. Most prevalent cases of arsenic toxicity have been reported from contaminated groundwater in alluvial plains and deltaic regions in Bangladesh and West Bengal, India, Nepal, Taiwan, Cambodia, Laos, Vietnam, North China, Hungary and Romania, where arsenic concentration in drinking water has been found to vary from 10 to >15,000 μg/L, far above the WHO and EPA recommended maximum level of 10 μg/L. In addition, inland basins in arid and semi-arid regions of the world (Argentina, Chile, Mexico, Nicaragua, Spain, and southwest United States) are also known to carry elevated levels of arsenic in groundwater, up to 21,000 μg/L. In mining areas arsenic levels, as high as 48,000 μg/L have been reported from Iron Mountain, California (United States). Geothermal waters in volcanic regions can also contain moderate to very high concentrations of arsenic. For example, arsenic concentrations in thermal waters at the Lassen Volcanic National Park and Yellowstone National Park in the United States are 150,000 and 7800 μg/L, respectively. Similarly, high values have been measured in volcanic regions in New Zealand (up to 9000 μg/L); Chile (from 45,000 to 50,000 μg/L); Ecuador (from 1000 to 7850 μg/L); and Japan (500 to 5900 μg/L).

Arsenic in groundwater mainly occurs in inorganic forms, namely arsenate, As^{5+} and arsenite As^{3+}, the latter being more toxic than the former. As^{5+}, the predominant species under atmospheric or more oxidizing environments in the pH range of 6–9, is thermodynamically stable and exists under mildly reducing conditions. As^{3+} is the most common species in anaerobic groundwater and is generally removed less efficiently than the oxidized As^{5+}. Groundwater pumped from shallow aquifers in Bangladesh and elsewhere upon coming in contact with O in the atmosphere converts into As-oxyanions that make it toxic.

Inorganic arsenic in the form of arsenate (As^{5+}) and arsenite (As^{3+}) are more common in water than organic arsenic. The occurrence is controlled by oxygen level of the water; As^{5+} is prevalent in oxygenated (aerobic) water, and As^{3+} is more common in hypoxic water (i.e., that with <2–3 ppm dissolved oxygen). Arsenicosis, or chronic arsenic toxicity (CAT), from drinking water derived from contaminated aquifers is a serious environmental health hazard throughout the world. Skin pigmentation and keratosis are the specific skin lesions characteristics of CAT; advance cases include chronic bronchitis, COPD, liver disease like non-cirrhotic portal fibrosis, peripheral vascular disease, hypertension and ischemic heart disease, diabetes mellitus, cancer of skin, lung and bladder.

Fluorine and Dental Health

It has been known for a long time that fluorine is beneficial for dental health. However, like all other trace elements, the beneficial aspect of fluorine is limited to a narrow range of concentration in the ingested food or water. Above this optimum range, fluorine becomes harmful and produces adverse effects on teeth and bones; similarly, its complete absence or concentration lower than the optimum is also harmful. Fig. 4 shows the dose-response curve for fluoride.

In the United States, standards for fluoridation of drinking water have been controversial and, due to the vested interests of industry and political pressures, standards have been revised at least three times: In 1975, under the Safe Drinking Water Act, the acceptable range of fluoride was set between 1.4 and 2.4 ppm. The Environmental Protection Agency revised the standard in 1985 and set the maximum contaminant level (MCL) for fluoride at 4 ppm, meaning that as long as the concentration remained below 4 ppm it would cause no harm. Most recently, in 2015, the U.S. Department of Health and Human Services revised the safe range from 0.7 to 1.2 ppm. By contrast, the guideline of 0.5 to 1.5 ppm fluoride in drinking water set by WHO in 1984 was twice reviewed in 1993 and 2004, but without any change in the guidelines.

In setting national standards for fluoride in water for human consumption, it is essential to consider the fluoride content of the municipal water supply system along with the intake of fluoride from other sources (e.g., from food grown on local soils, ambient level of fluoride in groundwater, etc.). Where the intakes are likely to approach, or be greater than, 6 mg/day, it would be appropriate to consider setting a standard at a concentration lower than 1.5 ppm. It should be noted that the recommended beneficial dose (concentration) for trace elements is subject to revision as more data become available from epidemiological studies, laboratory, and/or clinical research.

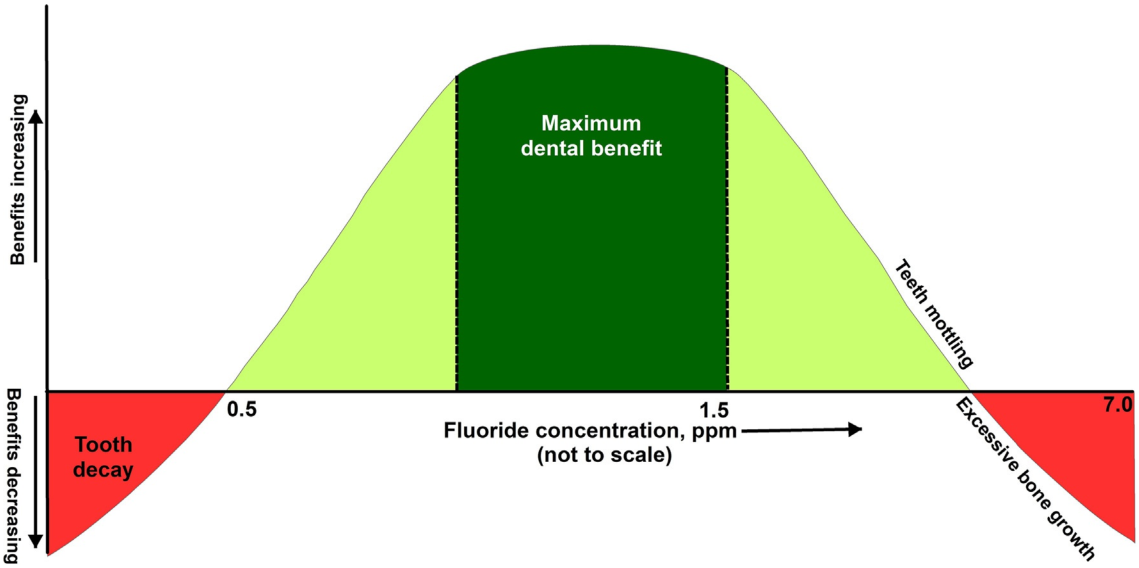

Fig. 4 Dose-response curve for fluoride.

Lead and Child Health

Of the many trace elements that affect human health, lead is one that is more dangerous and harmful to children than adults. The most vulnerable stage for harm by lead exposure is between the time when a developing fetus is 6 months old until the point when the child attains 6 years of age. Lead within pregnant woman's body easily permeates into the developing baby in the womb and, if the baby grows up in a home or neighborhood (playground, school) environment having elevated lead levels, the child is likely to become a victim of lead poisoning. Lead can damage the central nervous system, kidneys, and impair neurobehavioral and physical development, which can result in retardation of mental development, stunted growth, decreased physical stature, and hearing loss.

Sources of lead in the developed environment include: coal- and gas-fired power plants, leaded paint (banned from household use in the United States in 1976), metals processing and steel production, waste disposal (notably incineration), and emissions from internal combustion engines using leaded gasoline. Reduction of lead in gasoline in the United States began in 1976 and was completely phased out from automobile fuel in 1987. Many other developed countries have also stopped using leaded gasoline in automobiles. Prohibiting the manufacture and use of leaded gasoline in automobiles in the United States has produced a dramatic reduction in blood lead level (BLL) from about 15 μg/dL to about 9.5 μg/dL, a decrease of 63% over the 7-year period from 1976 to 1982.

Setting a safe level for Pb in humans has undergone many revisions, which serves as a good example of how definitions of "elevated BLLs" in the United States have changed over the years as more reliable data from chemical and epidemiological studies, and improved laboratory techniques, have become available (Fig. 5).

Lead is one of the most toxic metals and produces adverse effects in humans, particularly children. Despite lowering safe levels of lead repeatedly and appropriation of an average of $36 million each year for the 18-year period (2000–18) in the United States, many children, particularly in poor urban areas, are still at risk of lead poisoning. According to the US Centers for Disease Control, in 2012 approximately 500,000 children had seriously elevated BLLs.

Chemical Elements and Animal Health

Like humans, animals also depend on trace elements to maintain their health. Deficiency or excess could be detrimental for animal health. Elements like calcium, cobalt, fluorine, manganese, molybdenum, cooper, zinc, selenium, and iodine, in the right amount, help maintain proper metabolism in animals. Their deficiency can cause a number of health problems and even death.

Marco Polo, during his travel around 1295, came across a locality in northwest China where his horses died from an unknown cause. Later it was found that selenium accumulating plants are common in this area that upon ingestion result in selenium toxicity in animals. It is also likely that selenium toxicity might have caused serious diseases to the sick cavalry of General George Custer's army that led to his defeat in June of 1876 at the Battle of the Little Big Horn in the northwestern United States. As reported by Hasan et al. (2013), one of the reasons for General Custer's defeat might be selenium poisoning of his cavalry horses and mules. The animals grazed for months on native legume *Astragalus bisulcatus*, which is known to be a selenium accumulating plant. This legume was in full bloom during the spring, at their most succulent and Se-enriched state when the animals grazed on them. Ingestion of high amounts of selenium resulted in Se toxicity in the animals making them weak, partially paralyzed, suffering from impaired vision, and locosis, which made them unfit to serve in the battle. In both cases, a local geochemical anomaly was responsible for the

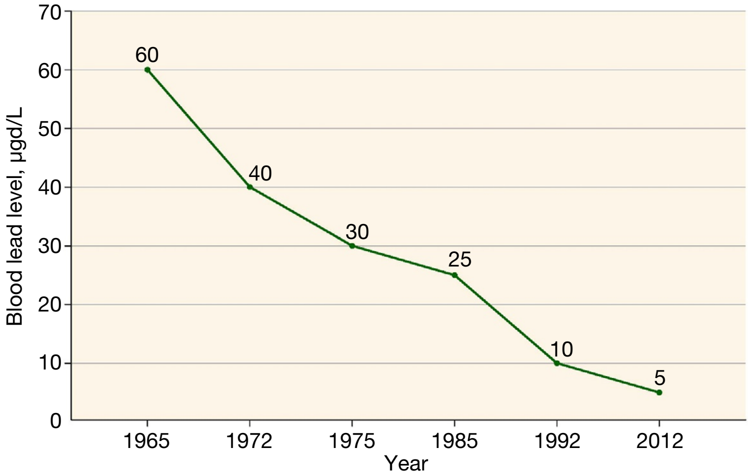

Fig. 5 Revision of elevated blood lead levels in children through the years.

animals' sickness. Excessive ingestion of selenium also leads to an acute toxic effect, called *blind staggers*, causing near blindness, and other nervous system diseases.

Wild animals migrate between different grazing areas to supplement essential nutrients that may be deficient at one location. Domesticated animals derive the nutrients from the feed that provide a balanced intake of essential nutrients. However, with the growing trend in organic farming, animals raised on such farms run the risk of nutrient imbalance because of the use of locally produced feed without chemical fertilizers. Farmers can overcome this problem by growing specific feed plants that accumulate the missing nutrient or exclude particular elements that cause nutritional imbalance. Jones (2013) offers a comprehensive discussion of trace elements in animal health, including variations due to species and breed differences, and recommended levels of common trace elements in various species.

Mineral Hot Springs and Balneotherapy

Balneotherapy is the use of mineralized water for treatment of diseases by bathing, generally at spas in mineral-rich thermal waters. It was an ancient form of medicine widely practiced since antiquity for treatment of various diseases. While there is no consensus on the classification of thermal springs based on temperature, a simple way to categorize hot springs is to use core human body temperature of 36.7 °C as a reference temperature for hot springs. Balneotherapists generally use the following classification:

- Cold springs: <25 °C,
- Tepid springs: 25–34 °C,
- Warm springs: 34–42 °C,
- Hot springs: >42 °C.

Hot springs at many spas all over the world draw a large number of people for treatment of many diseases, such as chronic rheumatism, central and peripheral neuropathy, gout, skin diseases, stress-related diseases, etc. Thermal springs with water temperature at or slightly above 20 °C are popular for soaking for several hours; however, care must be taken when using thermal waters above 30 °C because of the risks of dehydration and overheating. Balneotherapy is not recommended for people suffering from cancer, CVD, and immune deficiency symptoms. Altman (2000) provides a detailed historical account of balneotherapy including the origin of hot water springs and extensive discussion of their therapeutic benefits.

Current Status of Medical Geology

Medical geology has made great strides in the past 40 years. From the modest efforts of a handful of geochemists in the early 1960s trying to decipher possible links between the natural geochemical environment and health of people in a given area to the establishment in 2006 of the International Medical Geology Association (IMGA), medical geology has matured to the point that it is now duly recognized as a viable field of study. Courses are being offered at universities in many countries of the world, and degree programs/concentration areas in medical geology have also been introduced at other institutions. Graduate programs are available at some universities and many master's and doctoral research projects have been successfully completed at many universities across the globe.

On a broader perspective, the emergence of planetary health, and initiatives by the Ecological Society of America, USGS, and American Geophysical Union (AGU) to understand and mitigate the impacts of local-to-global scale environmental change on human and ecological health, has opened up additional avenues for collaboration between medical geologists and health professionals, lawmakers, and policy enforcers.

A solid foundation for medical geology is now in place, enabling it to move forward at a rapid pace. Publication of excellent textbooks, reference works, conference proceedings, professional newsletters, and the dedicated journal *GeoHealth*, along with many annual professional meetings, are key resources that provide valuable support to educational programs in medical geology at all levels. Medical geology is well poised to make useful contributions in training future generations of professionals to unravel the link between the natural environment and human health for the betterment of the global society. Table 3 provides a list of educational and professional resources.

Future Prospects

Several emerging environmental health concerns, such as COVID-19, climate change impacts, air pollution, pharmaceuticals and personal care products (PPCPs), and plastics, along with legacy contaminants such as lead, are some of the areas where medical geology can make valuable contributions. Medical geologists should collaborate with other scientists including experts in humanities, behavioral, and social sciences to find solutions to the problems and develop ways to eliminate or minimize the adverse impacts. A brief discussion of some of the main pollutants and research prospects are presented below.

Plastics, including microplastics (minute pieces of plastic <5 mm long) have become ubiquitous throughout the world and are present in the air, in terrestrial soils and water bodies, and in the ocean. As a consequence, microplastics are present in food consumed by animals and humans. Current knowledge about the health effects of plastics is very limited. Medical geologists can evaluate the fate and impacts of harmful chemicals, such as toxic metals, dioxins, and pesticides and other pollutants that adhere to microplastics. The ultimate fate of microplastics in the environment, along with health problems caused by ingestion or inhalation of microplastics also requires thorough investigation and advice on preventive measures.

Table 3 Educational and professional resources in medical geology.

A. Books
   1. *Progress in Medical Geology* (2017). Mori, I; and Ibaraki, H. (eds.). Cambridge Scholars Publishing, 329 p.
   2. *Essentials of Medical Geology* (2013). Selinus, O; et al. (eds.). Revised Edition, Springer, 805 p.
   3. *Medical Geology: Impacts of the Natural Environment on Public Health*. (2016). Centeno, J.S; Finkelman, R.B; and Selinus, O. 256 p. [Originally published in *Geosciences*; book published by MDPI, Basel, Switzerland].
   4. *Medical Geology–A Regional Synthesis* (2010). Selinus, O; Centeno, J. A; and Finkelman, R. B. Springer, 392 p.
   5. *Medical Geochemistry: Geological Materials and Health* (2013). Censi, P; Darrah, H; and Erel, Y. (eds.), Springer, 200 p.
   6. *Introduction to Medical Geology: Focus on Tropical Environments* (2009). *Dissanayake, C.*B; and Chandrajith, R. Springer. 297 p.
   7. *Medical Geology: Closing the Gap* (2003). Skinner, H.C. W; and Berger, A. R. Oxford University Press, 192 p.
   8. *Environmental Life Elements and Health* (1990). Tan, J; Peterson, P.J; and Wang, W. (eds.), Science Press, Beijing, China, 390 p.
   9. *Geomedicine* (1990), J. Lag (ed.) CRC Press, 448 p.

B. Journals
   1. *GeoHealth*, published by the American Geophysical Union (AGU).
   2. *Journal of Environmental Science and Health Part C*. Published by Taylor and Francis
   3. *Geopollution Science Medical Geology and Urban Geology*, published by the Japanese Society of Geopollution Science Medical Geology and Urban Geology (PMUG)
   4. *Environmental Toxicology and Chemistry*, published by the International Society for Environmental Toxicity and Chemistry (SETAC)
   5. *Environmental Geochemistry and Health*. Published by the Society for Environmental Geochemistry and Health
   6. Several other journals, notably, *AMBIO* (Sweden), *Elements* (United States), *Minerals* (Switzerland), *Earthwise* (United Kingdom), *Geosciences* (France), *Terrae* (Brazil), *Reviews in Mineralogy and Geochemistry*, *Science of the Total Environment*, *Ecotoxicology and Environmental Safety*, have published special issues on medical geology

C. Newsletters, published by the:
   1. International Medical Geology Association
   2. U.S. Geological Survey
   3. Geology & Health Division of the Geological Society of America

D. Conference Proceedings. Numerous proceedings of conferences held at international venues and covering medical geology topics, dating back to the 1960s, including 25 annual meetings organized by the erstwhile Environmental Trace Substances Center (United States)

E. Professional Organizations
   1. International Medical Geology Association, established in 2004 has 28 chapters in various countries across the globe to promote medical geology
   2. Society for Environmental Geochemistry and Health
   3. Geological Society of America: Geology and Health Division
   4. American Geophysical Union: Geohealth Section.

F. Miscellaneous
   1. Numerous doctoral dissertations and national geochemical and health atlases published in many countries.

Climate change presents another opportunity for medical geology research. Recent increase in the frequency and intensity of flooding and drought resulting from climate change causes physical injuries, deaths, and mental disease. Air and water pollution are likely to increase due to climate change, leading to substantial increases in pollution-related health problems. It is known that drought induces cracks in soil and reduces its water retention capacity. In extreme weather events, when drought is followed by heavy rainfall, infiltration decreases, sending runoff loaded with contaminants into clean or uncontaminated areas. Additionally, since drought causes greater water evaporation, a contaminated water body would experience higher concentrations of toxic substances, seriously degrading the quality of the remaining water. People drinking such water will be prone to serious health problems, unless timely intervention is made to provide alternative water supply.

Major flooding from intense rainstorms would render toxic waste facilities, dumps, mine tailings, agricultural sewage ponds, and chemical storage tanks that were previously safe from flooding unsafe. Inundation of these facilities would lead to release and transport of contaminates farther away. Thus, a re-evaluation of flood risk potential for such sites is required. This is another area where medical geologists and earth scientists can make valuable contributions.

Pollution is a hidden killer, it is slow, often imperceptible, but deadly, if not remediated in a timely manner. Pollution has become a serious health issue globally and it is estimated to be responsible for 8.3 million premature deaths annually and ranks at the top of environment-related deaths. Pollution and pollution abatement are serious challenges to modern society, but the issue is inadequately addressed in the development agendas of many countries and has not yet received substantial attention in global environmental health discussions. While traditional pollution, which includes water pollution from unsafe sanitation and use of biofuels in poorly ventilated homes, is mainly responsible for premature deaths in developing countries, industrial and urban pollution, which include soil and chemical pollution, ambient air pollution, and workplace pollution (called “modern pollution”), are the main causes of pollution-related mortality in developed countries. Traditional pollution decreases as economic conditions improve, but modern pollution is on the increase. One estimate puts the annual number of premature deaths from modern pollution at 5.3 million deaths (Fuller et al. 2019). The poorly understood but complex relationship between pollution, health, and climate change opens up new research avenues for medical geologists.

Phasing out leaded gasoline has cut down BLL significantly; however, other sources of lead that include active and abandoned mining, smelting, and manufacturing facilities; battery recycling, and lead-glazed pottery, have not been adequately studied and their health impact is not fully evaluated. Similarly, mercury emitted from coal-fired power plants, and artisanal gold mining in many developing countries impacts human health and the environment and calls for systematic research. The health impacts of PPCPs and radionuclides are also not well known and require focused research.

Combining satellite data with GIS in mitigating water-borne and other diseases is being successfully implemented, as with cholera and flooding in Bangladesh (Akanda et al., 2018). It is expected that combining the tools of artificial intelligence (AI) with remote sensing data and the widespread availability of mobile phones would lead to innovative solutions to global health problems. Drones can be deployed to map inaccessible areas to investigate possible sources of pollution. Medical geologists should play active roles in all these programs.

The current COVID-19 pandemic that is ravaging the world with about 3 million infected cases and 276,001 deaths (as of May 8, 2020) has devastated modern life and brought the global economy to a standstill. While intense research is underway all over the world to answer key questions about the novel virus mode of transmission, best clinical practice, and development of a vaccine, the number of infection and death is climbing. The pioneering undertaking named *Coronavirus Resource Center* operated by the Johns Hopkins University, USA; is tracking the spread of COVID-19 in real time. Experts from medical sciences (virology, infectious disease, epidemiology, emergency medicine, and related specialties) and earth sciences (GIS, remote sensing, climate science, etc.) are collaborating to provide valuable information on a continuing basis. Additionally, new findings are being reported and shared by researchers every day. Rita Colwell, founding editor of *GeoHealth*, has developed a predictive model for SARS-CoV-2, the virus that causes COVID-19, to track future outbreaks of the disease using satellite data and geoinformatics (Broom, 2020).

Geochemistry can continue to offer deep insights into human, animal, and plant health as all of them comprise major, minor, and trace elements. Their bioavailability and distribution are critical for a healthy life. Medical geologists should expand their studies to unravel trace elements roles at the cellular level in living organisms.

A major challenge for medical geology is the greater involvement of health care professionals. Despite the fact that physicians and others from the health science fields are increasingly attending major medical geology meetings, the number is still low. Medical geologists should actively seek collaboration in research projects by offering lectures and seminars at medical institutions and conferences, and getting more engaged with public health agencies. Inclusion of coursework in medical geology for health care professionals in their academic training should be given priority.

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https://tox21.gov/—Tox21 Program for rapid testing of toxicity of chemicals.

https://www.atsdr.cdc.gov/substances/index.asp—Toxic profile of 1000s of chemicals maintained by the Agency for Toxic Substances & Disease Registry (ATSDR).